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Final Technical Report for NASA Grant NAG-5-1088 entitled

"Studies in the Parameterization of Cloudiness in Climate Models and the Analysis of Radiation Fields in General Circulation Models"

Grant Period: October 1, 1988 to December 31, 1989

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(NASA-CR-186378) STUDIES IN THE PARAMETERIZATION OF CLOUDINESS IN CLIMATE MODELS AND THE ANALYSIS OF RADIATION FIELDS IN GENERAL CIRCULATION MODELS Final Technical Report, 1 Oct. 1988 - 31 Dec. 1989 G3/47

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1. Introduction

The grant was initiated on October 1, 1988 and continued through December 31, 1989. During the grant period, there were two major streams of investigation. First, broad-band parameterizations for atmospheric radiative transfer were developed for clear and cloudy skies. These were in the shortwave and longwave regions of the spectrum. These models were compared with other models in an international effort called ICRCCM (Intercomparison of Radiation Codes for Climate Models). This work had several benefits for the second stream of research pursued under this grant. In collaboration with Professor David Randall of Colorado State University (CSU), the radiation package developed in this research was used for simulations of a General Circulation Model (GCM). The following sections provide a synopsis of the research accomplishments in the two areas separately. Details are available in the published literature enumerated in Section 4.

2. Radiation Parameterization

The shortwave radiation parameterization currently used in the CSU GCM was enhanced to include absorption by carbon dioxide and oxygen. These gases contribute a small but, at some levels, significant amount to the total solar absorption. The results are shown in a series of tables labeled Table 1 (a) - (f). All cases use the standard Midlatitude Summer profile. The surface albedo is 20% and the solar zenith angle, 30° except for 1f. Tables 1 a and b show that oxygen alone absorbs less than 0.3% of the solar energy for this case and carbon dioxide only absorbs 0.5%. However, the peak heating rate due to CO_2 and O_2 is more than 0.3 C day^{-1}. Comparison of Tables 1 b and c show that doubling CO_2 will increase the absorption to just over 0.6%. Tables 1 e and f show the solar absorption for all constituents at two zenith angles. Notice that the system albedo increases from 17.9% to 22.6% when the zenith angle increase from 30° to 75°. This is due to enhanced Rayleigh scattering. These and other results are being submitted to ICRCCM for comparison with other codes.

The longwave radiation parameterization used in the GCM has been tested extensively against highly accurate line-by-line computations. This was also performed under the auspices

of ICRCCM and has resulted in a publication that has been submitted to a special issue of the *Journal of Geophysical Research* (Ridgway et al., 1990). Some results from that paper are presented here. Table 2 shows the flux comparisons at the surface, tropopause and top of the atmosphere. The parameterized model is labeled GLA/par while the two line-by-line models are from the Laboratory for Atmospheres, Goddard Space Flight Center (GLA/l-b-l) and the NOAA Geophysical Fluid Dynamics Laboratory (GFDL/l-b-l). The largest discrepancy is for the Ozone only case with a large underestimate of the downward flux. This is primarily because the 14 μm band is not included in this model. When all gases are present, this absorption feature is completely swamped by the 15 μm CO_2 band.

The flux comparison does not provide sufficient information in evaluating the performance of the model in a GCM. For this one needs to compare atmospheric cooling rate profiles. Selected examples are shown in Figures 1 (a) - (h). The parameterized model is again compared with two line-by-line models. It should be noted that the GLA l-b-l model has a nominal top at 0.1 mb and cooling rates from that model are not at all accurate above about 0.5 mb. The parameterized model performs successfully everywhere except for a tendency to underestimate the cooling rate in the vicinity of the stratopause. As the current application of the parameterized model is restricted to essentially tropospheric and lower stratospheric models, this is not a severe problem. The cooling rates obtained in a model run will be somewhat different from that shown in the figures since the vertical resolution of the model is typically much coarser than used for these comparisons. However, the problem of resolution will exist even for sophisticated models.

Apart from being quite accurate, the radiation parameterization when coded for use on a vector computer is very efficient. This has enable us to call the radiation routine in the GCM every hour, thus resolving the diurnal cycle.

3. General Circulation Model

The radiation parameterization was used in several GCM runs to study the effect of clouds on the general circulation. The results were published in two companion papers.

Abstracts are included as an appendix to this report. Some key elements of the papers are presented here.

Figure 2 shows the simulation of the outgoing longwave radiation and the albedo from the model and Nimbus 7 observations. Note that clear sky simulations are also given. This is an interesting and important feature of the radiation code. It is possible to compute the clear sky fluxes along with the actual radiation computations simultaneously. This enables us to compute the cloud radiative forcing (CRF) which is shown in Figure 3. The CRF is an indication of the influence of clouds on the radiation budget. The CRF at the top of the atmosphere can ultimately be verified with the results of the Earth Radiation Budget Experiment (ERBE).

In order to isolate the effects of clouds, the GCM was run without geography or topography, i.e. an all ocean planet. The control run used the radiative fluxes computed by the model with clouds whereas the NOACRF run did not consider clouds in the atmosphere for radiative purposes. Figure 4 shows the results in the two cases for precipitation and evaporation. The globally averaged precipitation and evaporation are about 15% greater in the cloudy run. Generally, the precipitation is much more concentrated in the cloudy run. Figure 5 shows that the cloudy run produces convection about 20% of the time in the tropics, while the cloud-free run produces almost incessant convection. It thus appears that ACRF favors more intense but less frequent convection. The mean meridional circulation differs quite substantially between the two simulations. As shown in Figure 6, both runs produce two Hadley cells - a weak cell in the Northern Hemisphere and a strong one straddling the equator, but with clouds, the main Hadley cell transports more mass and is more Earth-like than that of the cloud-free simulation.

4. Publications

Several publications stemming from this and related research have already appeared or are in various stages of publication. They are listed below and abstracts are attached to this report as an appendix.

Harshvardhan, D.A. Randall, T.G. Corsetti and D.A. Dazlich, 1989: Earth radiation budget and cloudiness simulations with a general circulation model. *J. Atmos. Sci.*, **46**, 1922-1942.

Randall, D.A., Harshvardhan, D.A. Dazlich and T.G. Corsetti, 1989: Interactions among radiation, convection and large-scale dynamics in a general circulation model. *J. Atmos. Sci.*, **46**, 1943-1970.

Ridgway, W.L., Harshvardhan and A. Arking, 1990: Computation of atmospheric infrared cooling rates by exact and approximate methods. Submitted to *J. Geophys. Res.*

Randall, D.A., Harshvardhan and D.A. Dazlich, 1990: Diurnal variability of the hydrologic cycle in a general circulation model. Submitted to *J. Atmos. Sci.*

Harshvardhan, D.A. Randall and D.A. Dazlich, 1990: Relationship between the longwave cloud radiative forcing at the surface and the top of the atmosphere. Submitted to *J. Climate*.

Table Captions

1. (a) Solar heating profile for a Midlatitude Summer case with only Oxygen absorption and Rayleigh scattering. Surface albedo is 0.2 and the solar zenith angle is 30°.
   (b) As in (a) except for 330 ppm of Carbon Dioxide.
   (c) As in (a) except for 660 ppm of Carbon Dioxide.
   (d) As in (a) except for Water Vapor, Carbon Dioxide and Ozone absorption.
   (e) As in (a) except for all gases.
   (f) As in (e) except for a solar zenith angle of 75°.
2. Flux comparisons for several ICRCCM cases. The models used are the parameterization in this study (GLA/par) and two line-by-line models from the Laboratory for Atmospheres, Goddard Space Flight Center (GLA/l-b-l) and the NOAA Geophysical Fluid Dynamics Laboratory (GFDL/l-b-l).

Figure Captions

1. (a) Infrared cooling rate profile for a Midlatitude Summer case for water vapor alone including the continuum. The three models are as in Table 2.
   (b) As in (a) except for a Tropical profile.
   (c) As in (a) except for 300 ppmv of carbon dioxide only.
   (d) As in (a) except for 600 ppmv of carbon dioxide only.
   (e) As in (c) except for a Subarctic Winter profile.
   (f) As in (c) except for ozone only.
   (g) As in (a) except for all gases.
   (h) As in (g) except for a Subarctic Winter profile.
2. The zonally averaged monthly mean January and July planetary albedo and OLR as simulated by the GCM, as observed by the Nimbus-7 scanner, and as simulated for the clear sky.
3. January (top row) and July (bottom row) zonally averaged cloud radiative forcing at the top of the atmosphere, at the Earth's surface, and across the atmosphere. In each panel, the dashed line is the solar CRF, the dotted line is the terrestrial CRF, and the solid line is the net CRF. Positive values are always in the sense of warming.
4. Zonally averaged precipitation, evaporation, and the difference, for both the clear and cloudy Seaworld simulation.
5. Zonally averaged frequency of cumulus convection, for both the clear and cloudy Seaworld simulations.
6. Mean meridional circulation for both Seaworld simulation.

O2 RAYL

SURFALB=0.2 SOLZEN=30

NO CLOUDS

MIDLATITUDE SUMMER

HEIGHT (KM)	PRESSURE (MB)	NET DOWNWARD FLUX (W/M**2)	ABSORBED FLUX (W/M**2)	HEATING RATE (CELSIUS/DAY)
TOA	0.00	915.11		
80.0	0.01	915.10	0.01	
75.0	0.03	915.10	0.00	0.06
70.0	0.07	915.10	0.00	0.05
65.0	0.13	915.10	0.00	0.06
60.0	0.25	915.10	0.00	0.06
55.0	0.49	915.09	0.00	0.06
50.0	0.95	915.09	0.00	0.06
45.0	1.76	915.08	0.01	0.06
40.0	3.33	915.07	0.01	0.06
35.0	6.52	915.05	0.02	0.06
30.0	13.20	915.00	0.05	0.06
25.0	27.70	914.90	0.10	0.06
24.0	32.20	914.87	0.03	0.06
23.0	37.60	914.83	0.04	0.06
22.0	43.70	914.78	0.04	0.06
21.0	51.00	914.73	0.05	0.06
20.0	59.50	914.67	0.06	0.06
19.0	69.50	914.60	0.07	0.06
18.0	81.20	914.52	0.08	0.06
17.0	95.00	914.42	0.10	0.06
16.0	111.00	914.31	0.11	0.06
15.0	130.00	914.17	0.13	0.06
14.0	153.00	914.01	0.16	0.06
13.0	179.00	913.83	0.18	0.06
12.0	209.00	913.62	0.21	0.06
11.0	243.00	913.39	0.23	0.06
10.0	281.00	913.13	0.26	0.06
9.0	324.00	912.84	0.29	0.06
8.0	372.00	912.52	0.32	0.06
7.0	426.00	912.16	0.36	0.06
6.0	487.00	911.76	0.40	0.06
5.0	554.00	911.76	0.00	0.00
4.0	628.00	911.76	0.00	0.00
3.0	710.00	911.76	0.00	0.00
2.0	802.00	911.76	0.00	0.00
1.0	902.00	911.76	0.00	0.00
0.5	955.90	911.76	0.00	0.00
0.0	1013.00	911.76	0.00	0.00

PLANETARY ALBEDO = 0.223

UPFSFC= 227.94 DNFSFC=1139.70 NETSFC= 911.76

UPFTOP= 262.95 DNFTOP=1178.05 NETTOP= 915.11

TABLE 1a

CO2 330 PPM RAYL

SURFALB=0.2 SOLZEN=30

NO CLOUDS

MIDLATITUDE SUMMER

HEIGHT (KM)	PRESSURE (MB)	NET DOWNWARD FLUX (W/M**2)	ABSORBED FLUX (W/M**2)	HEATING RATE (CELSIUS/DAY)
TOA	0.00	915.76		
80.0	0.01	915.75	0.01	
75.0	0.03	915.75	0.00	0.00
70.0	0.07	915.75	0.00	0.00
65.0	0.13	915.75	0.00	0.00
60.0	0.25	915.75	0.00	0.01
55.0	0.49	915.75	0.00	0.02
50.0	0.95	915.75	0.00	0.03
45.0	1.76	915.74	0.01	0.06
40.0	3.33	915.72	0.02	0.11
35.0	6.52	915.65	0.07	0.18
30.0	13.20	915.45	0.20	0.25
25.0	27.70	915.03	0.43	0.25
24.0	32.20	914.91	0.12	0.22
23.0	37.60	914.77	0.14	0.21
22.0	43.70	914.63	0.14	0.20
21.0	51.00	914.46	0.16	0.19
20.0	59.50	914.29	0.18	0.18
19.0	69.50	914.09	0.19	0.16
18.0	81.20	913.88	0.21	0.15
17.0	95.00	913.65	0.23	0.14
16.0	111.00	913.40	0.25	0.13
15.0	130.00	913.12	0.28	0.12
14.0	153.00	912.81	0.31	0.11
13.0	179.00	912.49	0.32	0.11
12.0	209.00	912.14	0.35	0.10
11.0	243.00	911.77	0.37	0.09
10.0	281.00	911.39	0.38	0.08
9.0	324.00	910.99	0.40	0.08
8.0	372.00	910.57	0.42	0.07
7.0	426.00	910.12	0.44	0.07
6.0	487.00	909.65	0.47	0.06
5.0	554.00	909.65	0.00	0.00
4.0	628.00	909.65	0.00	0.00
3.0	710.00	909.65	0.00	0.00
2.0	802.00	909.65	0.00	0.00
1.0	902.00	909.65	0.00	0.00
0.5	955.90	909.65	0.00	0.00
0.0	1013.00	909.65	0.00	0.00

PLANETARY ALBEDO = 0.223

UPFSFC= 227.41 DNFSFC=1137.07 NETSFC= 909.65

UPFTOP= 262.29 DNFTOP=1178.05 NETTOP= 915.76

TABLE 1b

CO2 660 PPM RAYL

SURFALB=0.2 SOLZEN=30

NO CLOUDS

MIDLATITUDE SUMMER

HEIGHT (KM)	PRESSURE (MB)	NET DOWNWARD FLUX (W/M**2)	ABSORBED FLUX (W/M**2)	HEATING RATE (CELSIUS/DAY)
TOA	0.00	916.09		
80.0	0.01	916.08	0.01	
75.0	0.03	916.08	0.00	0.00
70.0	0.07	916.08	0.00	0.00
65.0	0.13	916.08	0.00	0.01
60.0	0.25	916.08	0.00	0.02
55.0	0.49	916.08	0.00	0.03
50.0	0.95	916.07	0.00	0.06
45.0	1.76	916.06	0.01	0.12
40.0	3.33	916.02	0.04	0.21
35.0	6.52	915.91	0.12	0.31
30.0	13.20	915.61	0.29	0.37
25.0	27.70	915.06	0.55	0.32
24.0	32.20	914.91	0.15	0.28
23.0	37.60	914.75	0.17	0.26
22.0	43.70	914.57	0.18	0.24
21.0	51.00	914.37	0.20	0.23
20.0	59.50	914.16	0.21	0.21
19.0	69.50	913.92	0.23	0.20
18.0	81.20	913.67	0.25	0.18
17.0	95.00	913.39	0.28	0.17
16.0	111.00	913.09	0.30	0.16
15.0	130.00	912.76	0.33	0.15
14.0	153.00	912.39	0.37	0.14
13.0	179.00	912.00	0.39	0.13
12.0	209.00	911.58	0.42	0.12
11.0	243.00	911.14	0.44	0.11
10.0	281.00	910.68	0.46	0.10
9.0	324.00	910.20	0.48	0.09
8.0	372.00	909.70	0.50	0.09
7.0	426.00	909.17	0.53	0.08
6.0	487.00	908.60	0.56	0.08
5.0	554.00	908.60	0.00	0.00
4.0	628.00	908.60	0.00	0.00
3.0	710.00	908.60	0.00	0.00
2.0	802.00	908.60	0.00	0.00
1.0	902.00	908.60	0.00	0.00
0.5	955.90	908.60	0.00	0.00
0.0	1013.00	908.60	0.00	0.00

PLANETARY ALBEDO = 0.222

UPFSFC= 227.15 DNFSFC=1135.75 NETSFC= 908.60

UPFTOP= 261.97 DNFTOP=1178.05 NETTOP= 916.09

TABLE 1c

H2O,CO2,O3 RAYL

SURFALB=0.2 SOLZEN=30

NO CLOUDS

MIDLATITUDE SUMMER

HEIGHT (KM)	PRESSURE (MB)	NET DOWNWARD FLUX (W/M**2)	ABSORBED FLUX (W/M**2)	HEATING RATE (CELSIUS/DAY)
TOA	0.00	966.25		
80.0	0.01	966.24	0.01	
75.0	0.03	966.23	0.01	2.99
70.0	0.07	966.21	0.02	4.34
65.0	0.13	966.17	0.05	6.27
60.0	0.25	966.04	0.13	9.01
55.0	0.49	965.68	0.35	12.64
50.0	0.95	964.77	0.91	16.70
45.0	1.76	962.82	1.95	20.36
40.0	3.33	959.30	3.51	18.90
35.0	6.52	955.32	3.99	10.55
30.0	13.20	950.66	4.65	5.88
25.0	27.70	945.12	5.54	3.22
24.0	32.20	943.93	1.19	2.24
23.0	37.60	942.67	1.26	1.97
22.0	43.70	941.42	1.25	1.74
21.0	51.00	940.12	1.29	1.50
20.0	59.50	938.88	1.24	1.24
19.0	69.50	937.69	1.18	1.00
18.0	81.20	936.60	1.10	0.79
17.0	95.00	935.60	1.00	0.61
16.0	111.00	934.69	0.91	0.48
15.0	130.00	933.81	0.88	0.39
14.0	153.00	932.92	0.89	0.33
13.0	179.00	932.07	0.85	0.28
12.0	209.00	931.15	0.92	0.26
11.0	243.00	929.65	1.49	0.37
10.0	281.00	926.26	3.39	0.75
9.0	324.00	919.50	6.76	1.33
8.0	372.00	909.44	10.07	1.77
7.0	426.00	897.11	12.33	1.93
6.0	487.00	885.74	11.37	1.57
5.0	554.00	874.80	10.95	1.38
4.0	628.00	859.29	15.51	1.77
3.0	710.00	839.10	20.19	2.08
2.0	802.00	818.18	20.92	1.92
1.0	902.00	795.49	22.68	1.91
0.5	955.90	781.68	13.81	2.16
0.0	1013.00	765.76	15.92	2.35

PLANETARY ALBEDO = 0.180

UPFSFC= 191.44 DNFSFC= 957.20 NETSFC= 765.76

UPFTOP= 211.80 DNFTOP=1178.05 NETTOP= 966.25

TABLE 1d

H2O,O3,CO2,O2 RAYL

SURFALB=0.2 SOLZEN=30

NO CLOUDS

MIDLATITUDE SUMMER

HEIGHT (KM)	PRESSURE (MB)	NET DOWNWARD FLUX (W/M**2)	ABSORBED FLUX (W/M**2)	HEATING RATE (CELSIUS/DAY)
TOA	0.00	967.04		
80.0	0.01	967.03	0.01	
75.0	0.03	967.02	0.01	3.06
70.0	0.07	967.00	0.02	4.40
65.0	0.13	966.96	0.05	6.33
60.0	0.25	966.82	0.13	9.07
55.0	0.49	966.47	0.36	12.70
50.0	0.95	965.55	0.92	16.76
45.0	1.76	963.59	1.96	20.42
40.0	3.33	960.07	3.53	18.96
35.0	6.52	956.06	4.01	10.61
30.0	13.20	951.36	4.70	5.94
25.0	27.70	945.71	5.64	3.29
24.0	32.20	944.49	1.22	2.30
23.0	37.60	943.19	1.30	2.03
22.0	43.70	941.89	1.30	1.80
21.0	51.00	940.55	1.35	1.56
20.0	59.50	939.24	1.30	1.30
19.0	69.50	937.99	1.26	1.06
18.0	81.20	936.81	1.18	0.85
17.0	95.00	935.71	1.10	0.67
16.0	111.00	934.69	1.02	0.54
15.0	130.00	933.68	1.01	0.45
14.0	153.00	932.63	1.05	0.39
13.0	179.00	931.59	1.03	0.34
12.0	209.00	930.46	1.13	0.32
11.0	243.00	928.74	1.73	0.43
10.0	281.00	925.09	3.65	0.81
9.0	324.00	918.04	7.05	1.38
8.0	372.00	907.65	10.39	1.83
7.0	426.00	894.96	12.69	1.98
6.0	487.00	883.20	11.77	1.63
5.0	554.00	872.25	10.95	1.38
4.0	628.00	856.74	15.51	1.77
3.0	710.00	836.55	20.19	2.08
2.0	802.00	815.63	20.92	1.92
1.0	902.00	792.95	22.68	1.91
0.5	955.90	779.14	13.81	2.16
0.0	1013.00	763.22	15.92	2.35

PLANETARY ALBEDO = 0.179

UPFSFC= 190.80 DNFSFC= 954.02 NETSFC= 763.22

UPFTOP= 211.01 DNFTOP=1178.05 NETTOP= 967.04

TABLE 1e

H2O,O3,CO2,O2 RAYL

SURFALB=0.2 SOLZEN=75

NO CLOUDS

MIDLATITUDE SUMMER

HEIGHT (KM)	PRESSURE (MB)	NET DOWNWARD FLUX (W/M**2)	ABSORBED FLUX (W/M**2)	HEATING RATE (CELSIUS/DAY)
TOA	0.00	272.59		
80.0	0.01	272.58	0.01	
75.0	0.03	272.57	0.01	2.98
70.0	0.07	272.55	0.02	4.30
65.0	0.13	272.51	0.05	6.12
60.0	0.25	272.38	0.12	8.52
55.0	0.49	272.07	0.31	11.08
50.0	0.95	271.40	0.67	12.31
45.0	1.76	270.41	0.99	10.37
40.0	3.33	269.13	1.27	6.84
35.0	6.52	267.52	1.61	4.27
30.0	13.20	265.36	2.17	2.74
25.0	27.70	262.35	3.00	1.75
24.0	32.20	261.66	0.69	1.29
23.0	37.60	260.93	0.74	1.15
22.0	43.70	260.19	0.74	1.03
21.0	51.00	259.41	0.77	0.90
20.0	59.50	258.66	0.75	0.75
19.0	69.50	257.94	0.72	0.61
18.0	81.20	257.27	0.67	0.49
17.0	95.00	256.65	0.62	0.38
16.0	111.00	256.08	0.57	0.30
15.0	130.00	255.52	0.56	0.25
14.0	153.00	254.93	0.58	0.21
13.0	179.00	254.36	0.57	0.19
12.0	209.00	253.69	0.67	0.19
11.0	243.00	252.46	1.23	0.30
10.0	281.00	249.69	2.77	0.61
9.0	324.00	245.32	4.37	0.86
8.0	372.00	241.06	4.26	0.75
7.0	426.00	237.00	4.06	0.63
6.0	487.00	231.90	5.10	0.71
5.0	554.00	226.43	5.48	0.69
4.0	628.00	220.62	5.81	0.66
3.0	710.00	214.16	6.46	0.67
2.0	802.00	205.72	8.43	0.77
1.0	902.00	196.57	9.16	0.77
0.5	955.90	192.21	4.35	0.68
0.0	1013.00	188.00	4.21	0.62

PLANETARY ALBEDO = 0.226

UPFSFC= 47.00 DNFSFC= 235.01 NETSFC= 188.00

UPFTOP= 79.49 DNFTOP= 352.07 NETTOP= 272.59

TABLE 1f

TABLE 2

Atmospheric Case	Flux Model	Surface Up (w/m^2)	Surface Down (w/m^2)	Tropopause Up (w/m^2)	Tropopause Down (w/m^2)	Top of Atmos. (w/m^2)
Tropical	GLA/par	459.29	386.72	337.51	2.16	337.80
H_2O	GLA/lbl	459.09	383.87	338.84	2.63	339.12
	GFDL/lbl	459.18	383.85	338.97	2.83	339.12
Mid-lat Sum.	GLA/par	423.48	262.23	336.28	5.26	336.27
H_2O	GLA/lbl	423.48	267.28	336.59	6.26	336.49
No continuum	GFDL/lbl	423.56	266.77	336.62	6.74	336.32
Mid-lat Sum.	GLA/par	423.48	331.27	327.71	6.26	327.70
H_2O	GLA/lbl	423.48	330.59	328.40	6.25	328.31
	GFDL/lbl	423.56	330.30	328.57	6.74	328.28
Mid-lat Sum.	GLA/par	423.48	75.33	384.59	12.32	385.21
CO_2	GLA/lbl	423.48	76.48	383.08	12.14	383.65
300 ppmv	GFDL/lbl	423.56	76.28	383.22	12.11	383.72
Mid-lat Sum.	GLA/par	423.48	82.91	379.89	14.44	381.31
CO_2	GLA/lbl	423.48	84.66	377.95	13.91	379.36
600 ppmv	GFDL/lbl	421.38	83.60	376.77	13.88	378.07
Mid-lat Sum.	GLA/par	423.48	4.20	420.60	2.15	414.20
Ozone	GLA/lbl	423.48	6.00	419.60	3.10	412.01
	GFDL/lbl	423.56	6.18	419.40	3.04	412.06
Mid-lat Sum.	GLA/par	423.48	341.77	296.67	19.48	291.19
$H_2O+CO_2+O_3$	GLA/lbl	423.48	343.07	295.32	20.80	290.45
	GFDL/lbl	423.56	343.27	295.25	21.34	290.32
Sub-arct Win.	GLA/par	247.95	43.55	232.14	14.83	230.63
CO_2	GLA/lbl	247.71	44.22	231.64	14.15	230.17
300 ppmv	GFDL/lbl	247.36	43.90	231.44	14.16	229.94
Sub-arct Win.	GLA/par	247.95	160.98	209.81	28.84	203.53
$H_2O+CO_2+O_3$	GLA/lbl	247.71	164.65	209.76	30.49	203.42
	GFDL/lbl	247.36	164.44	209.35	31.27	202.95

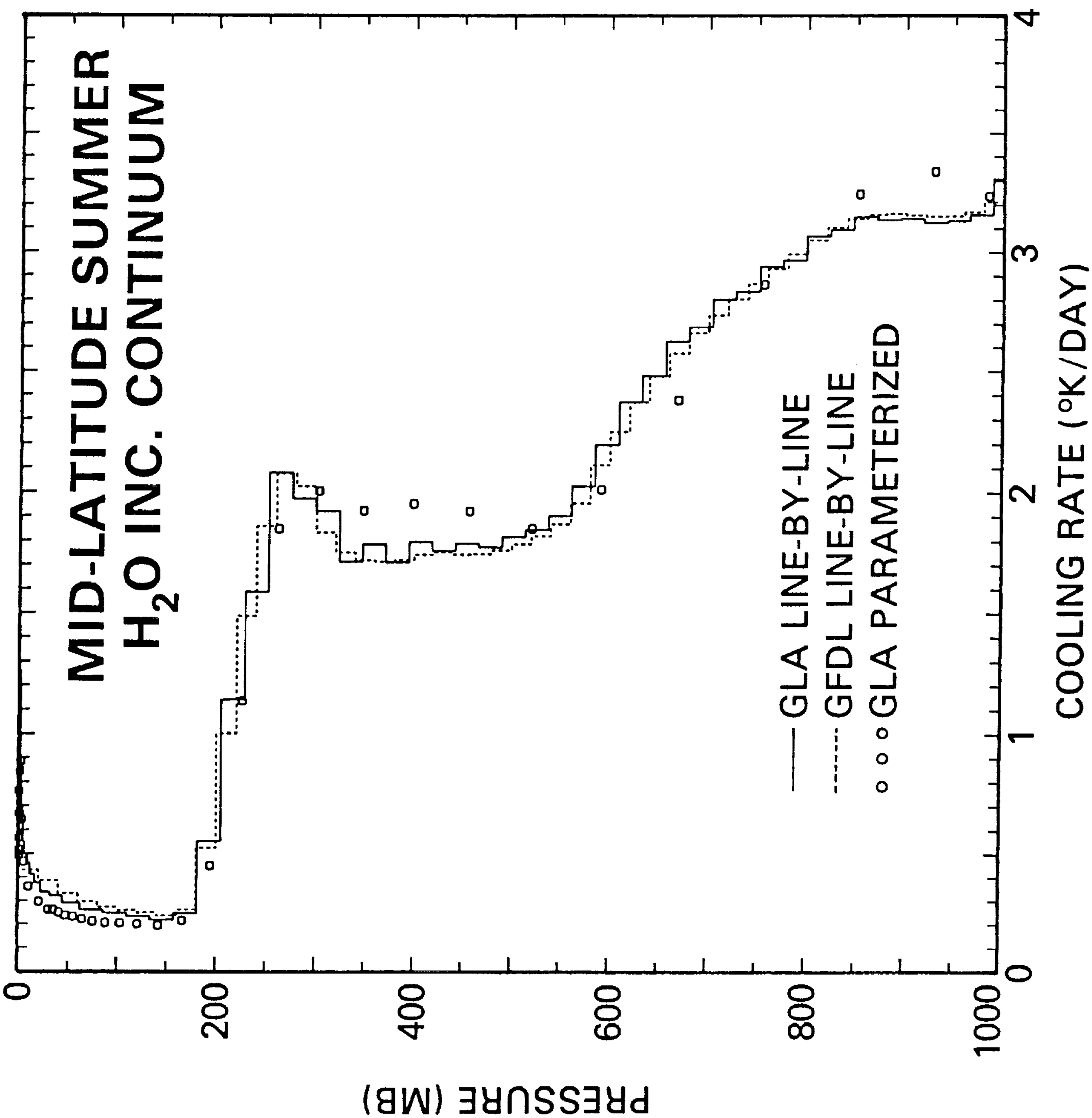

MID-LATITUDE SUMMER
H_2O INC. CONTINUUM
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0
1
2
3
4
0
200
400
600
800
1000

FIGURE 1a

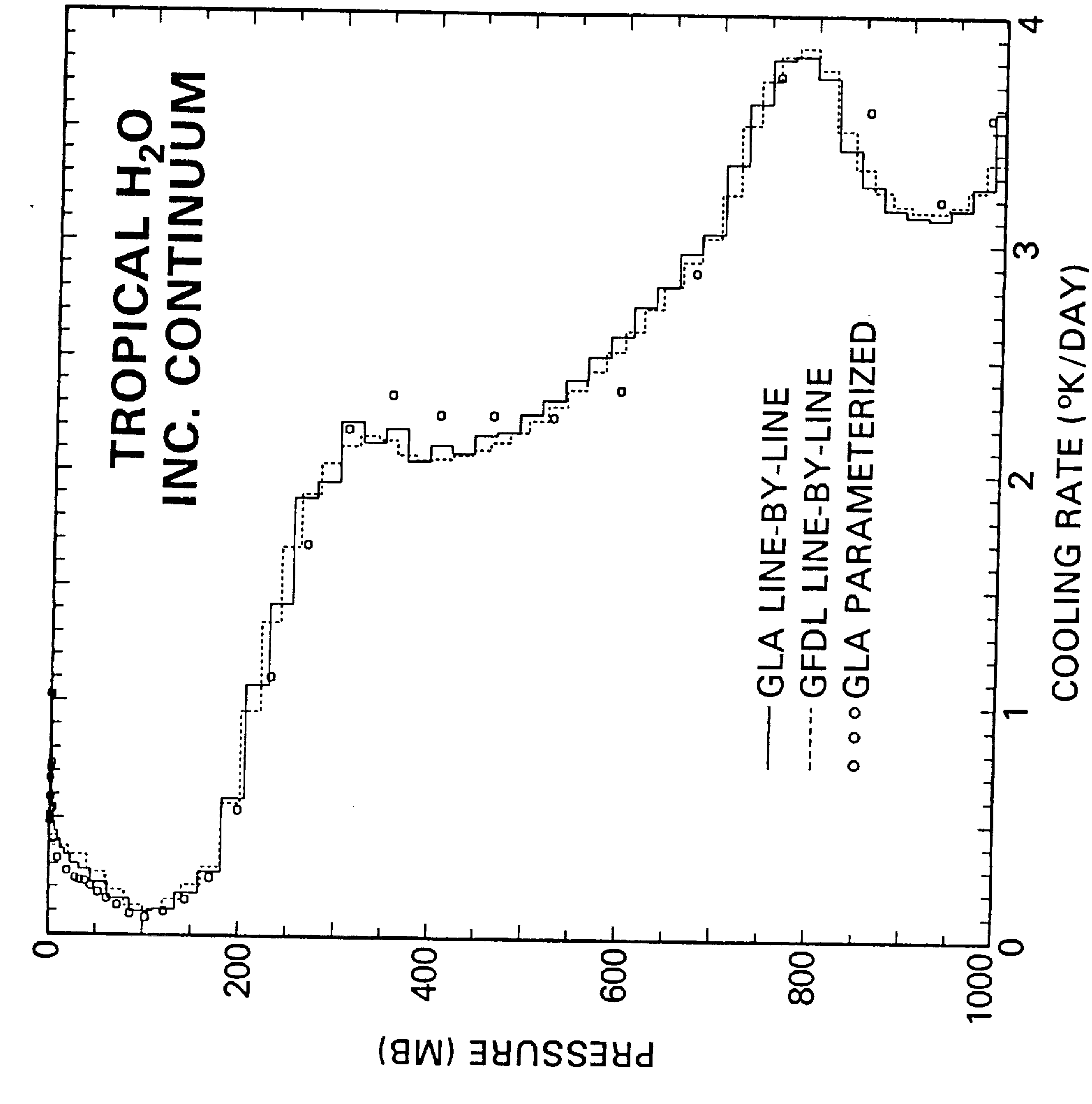

TROPICAL H_2O
INC. CONTINUUM
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0
1
2
3
4
0
200
400
600
800
1000

FIGURE 1b

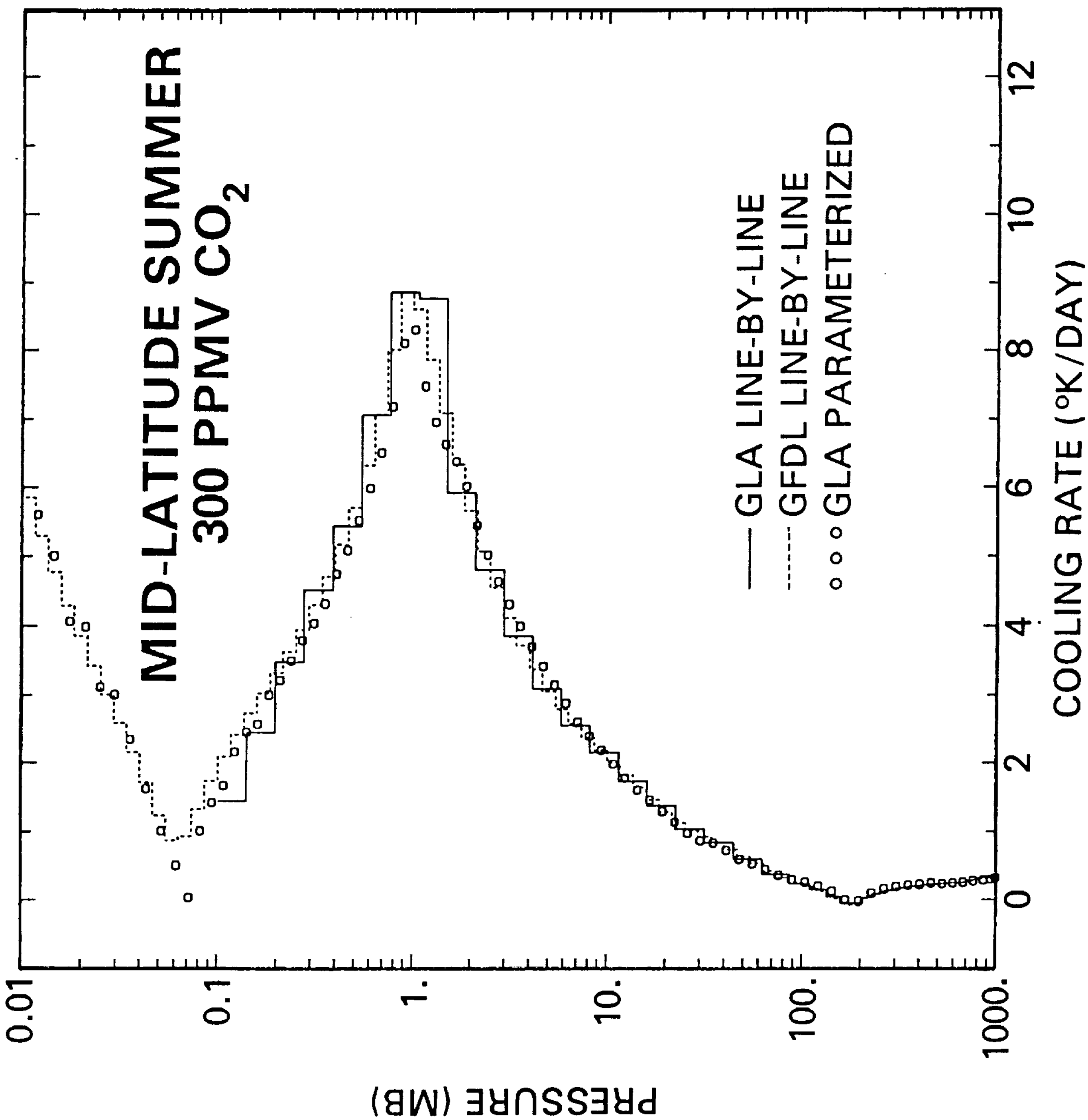
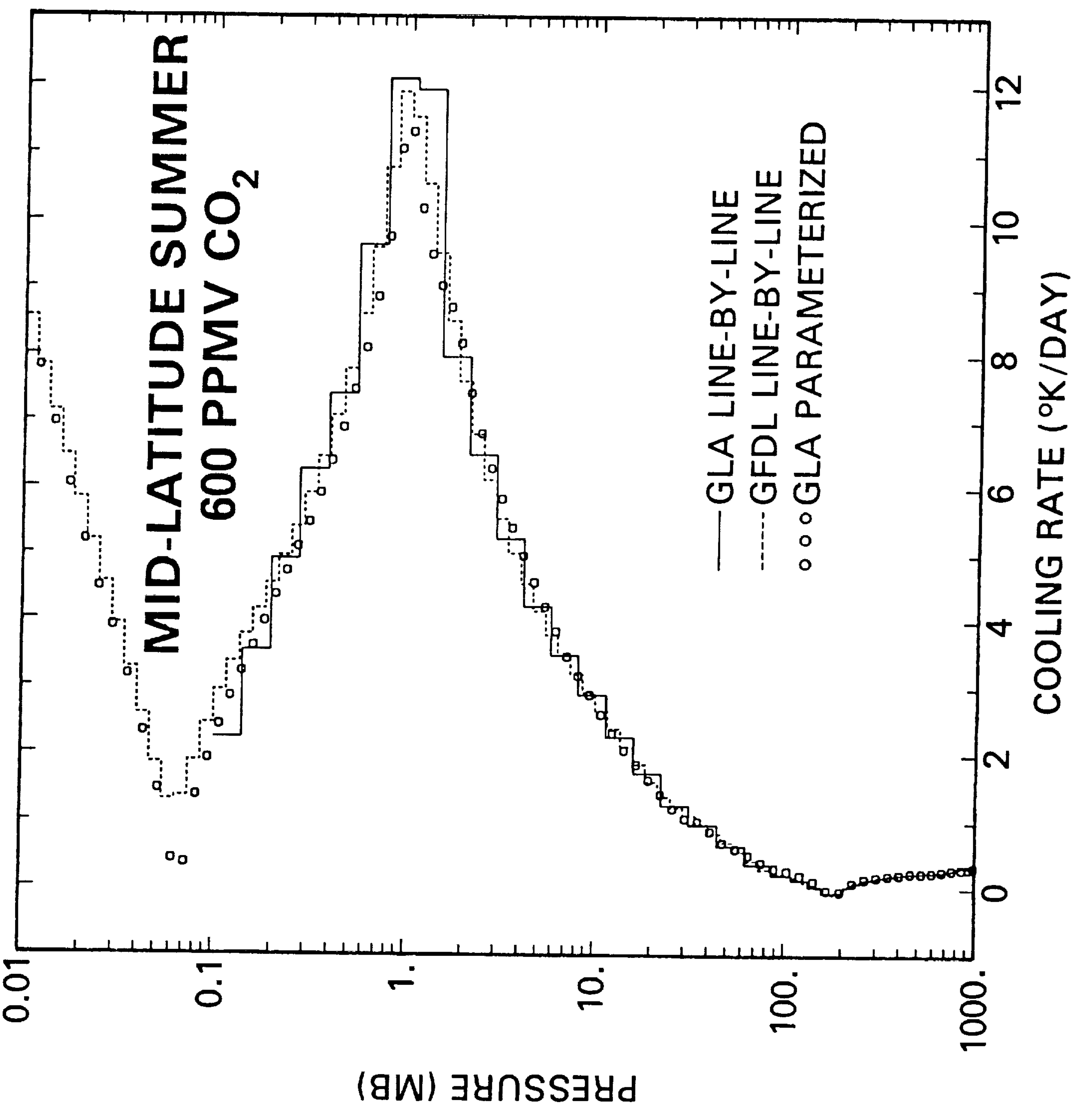

MID-LATITUDE SUMMER
300 PPMV CO_2
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0.01
0.1
1.
10.
100.
1000.
0
2
4
6
8
10
12

FIGURE 1c



MID-LATITUDE SUMMER
600 PPMV CO_2
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0.01
0.1
1.
10.
100.
1000.
0
2
4
6
8
10
12

FIGURE 1d

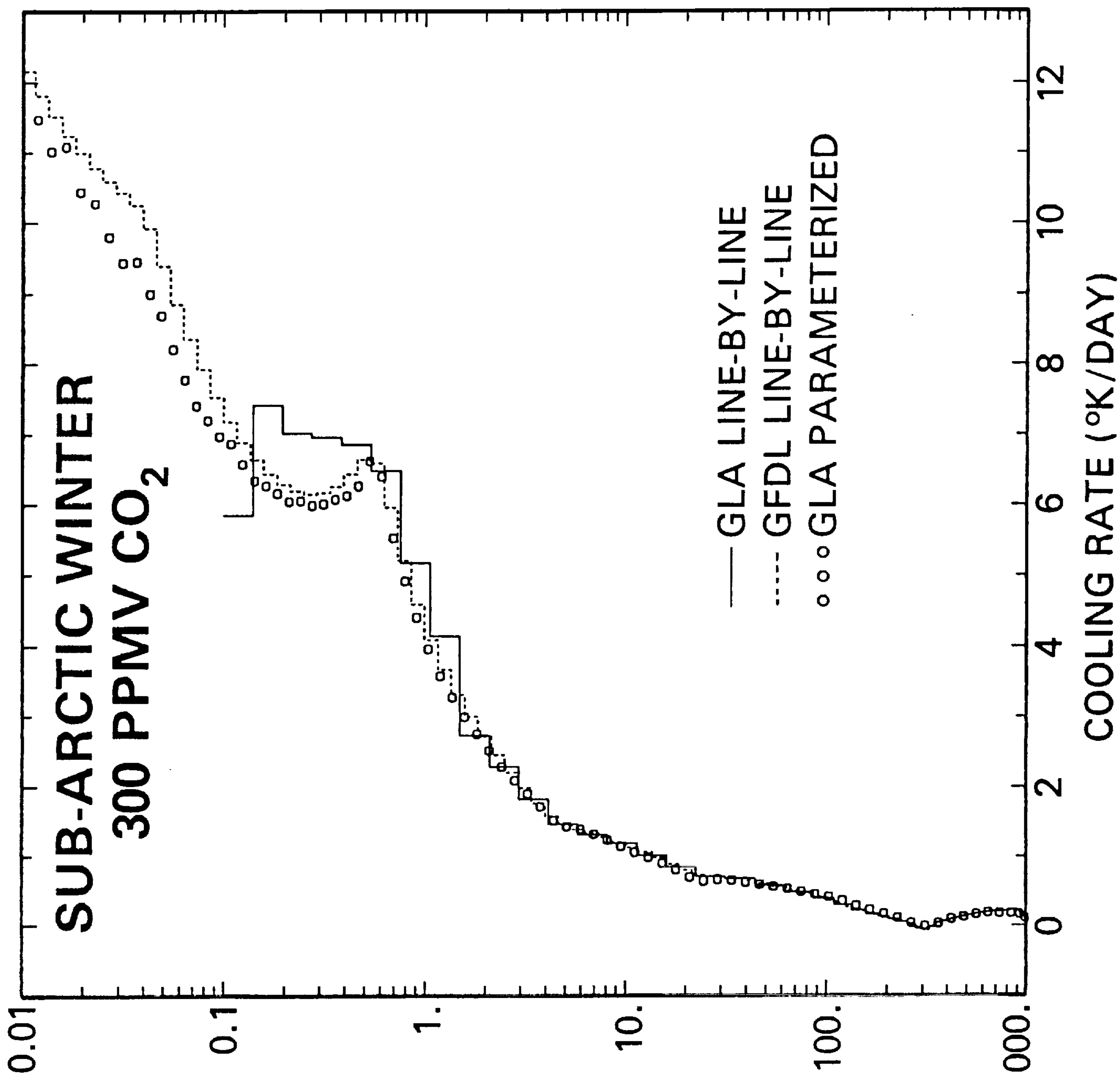

SUB-ARCTIC WINTER
300 PPMV CO_2
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0.01
0.1
1.
10.
100.
1000.
0
2
4
6
8
10
12

FIGURE 1e

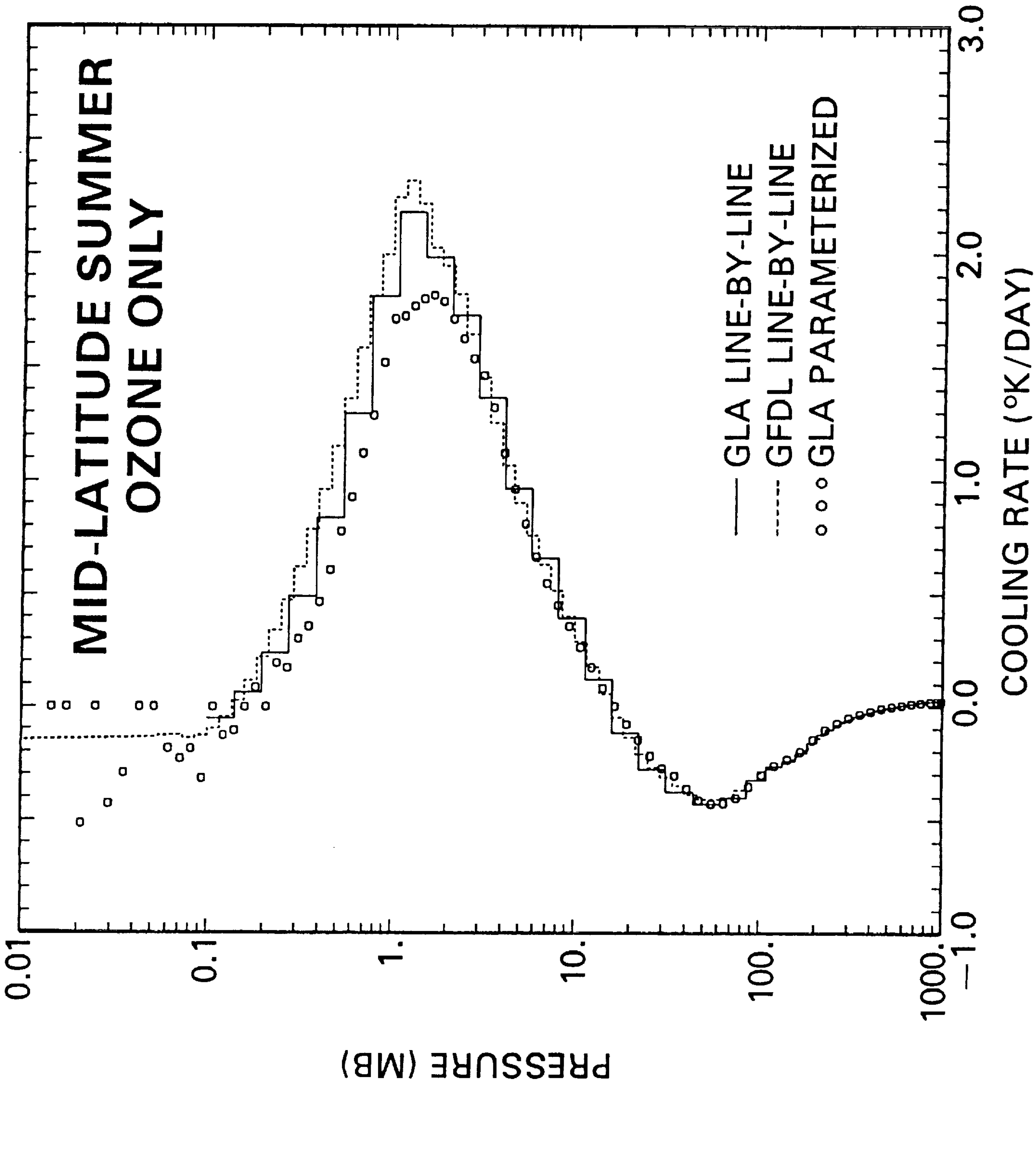

MID-LATITUDE SUMMER
OZONE ONLY
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0.01
0.1
1.
10.
100.
1000.
−1.0
0.0
1.0
2.0
3.0

FIGURE 1f

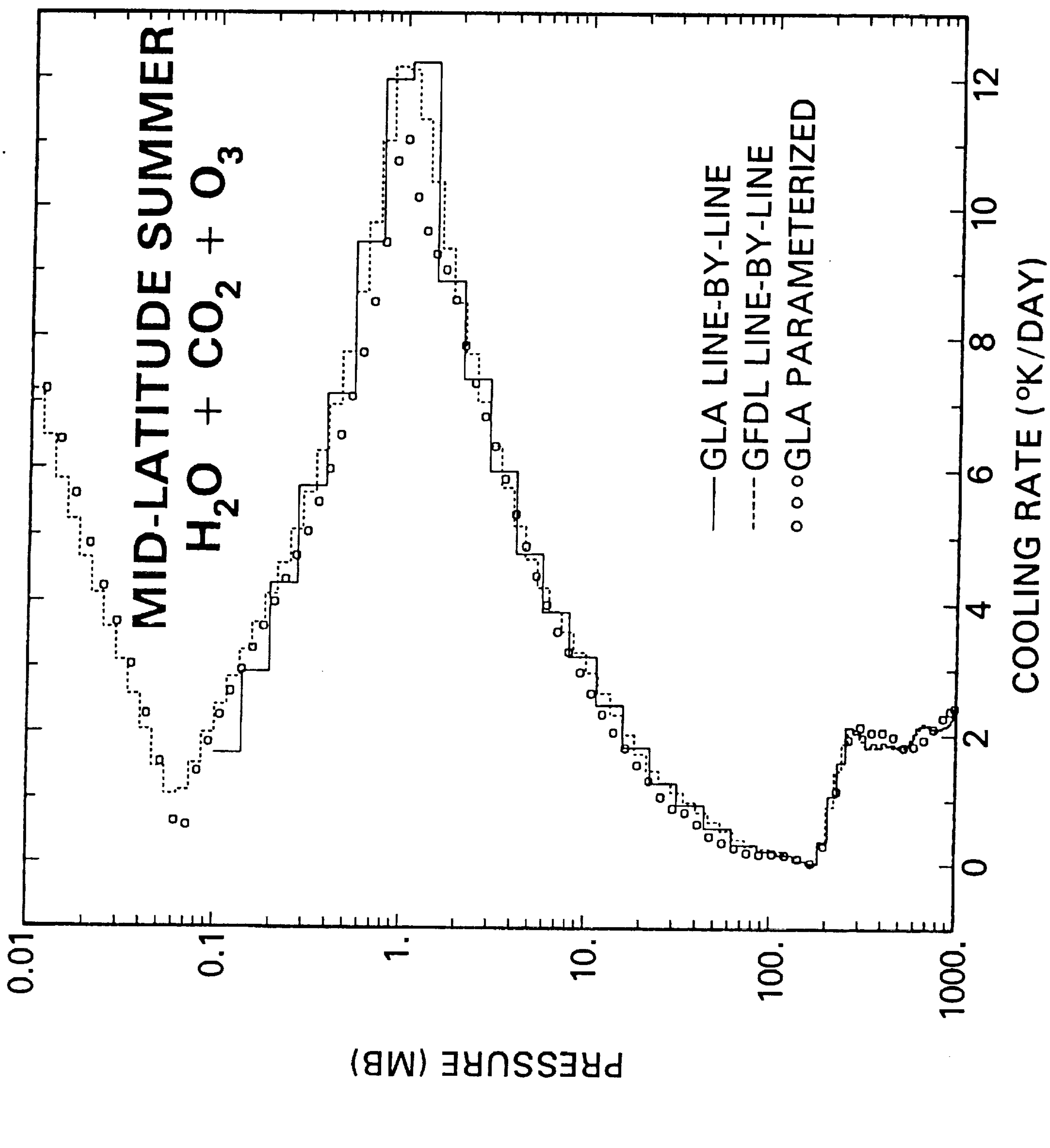

MID-LATITUDE SUMMER
H_2O + CO_2 + O_3
GLA LINE-BY-LINE
GFDL LINE-BY-LINE
GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0.01
0.1
1.
10.
100.
1000.
0
2
4
6
8
10
12

FIGURE 1g

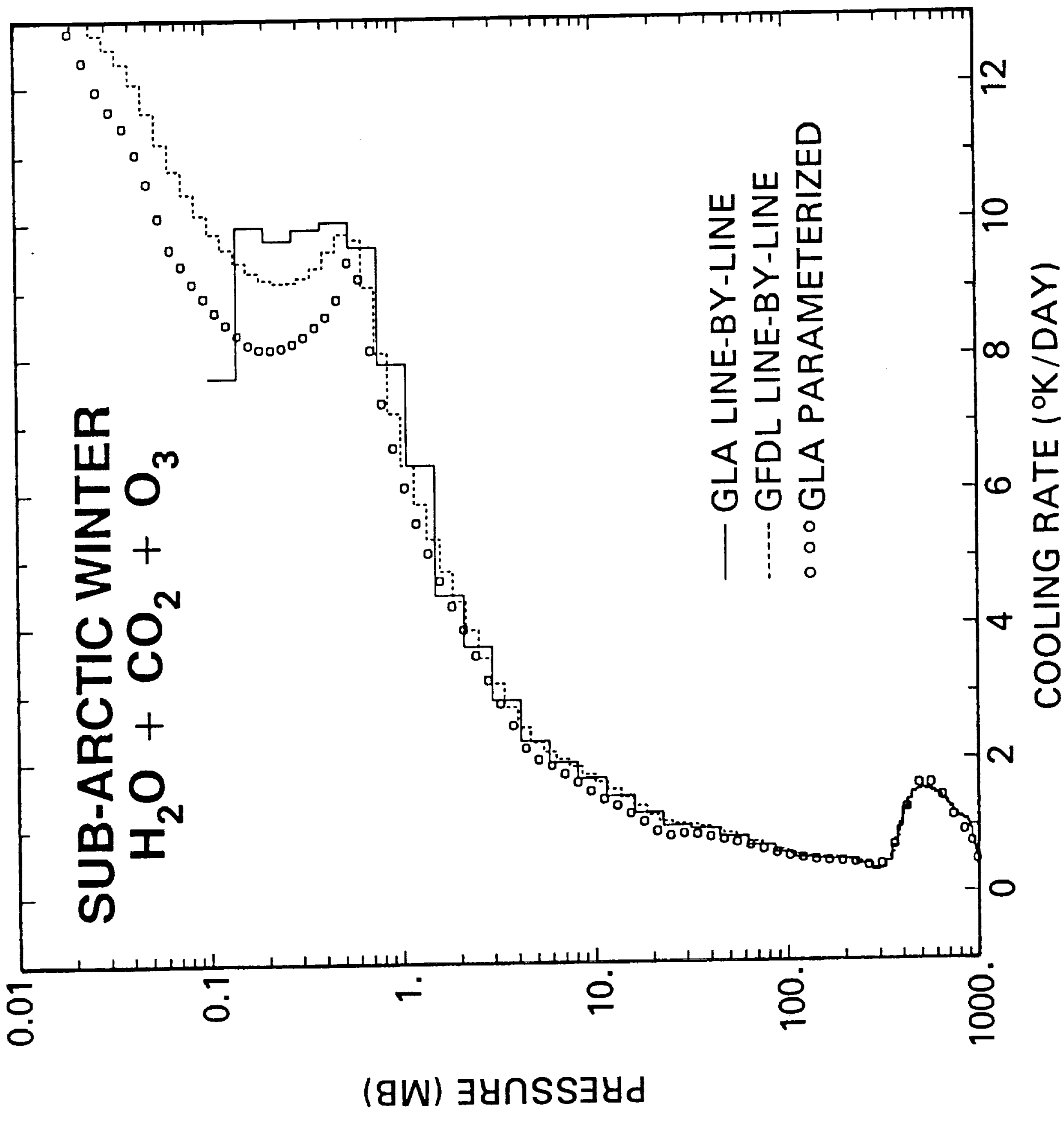
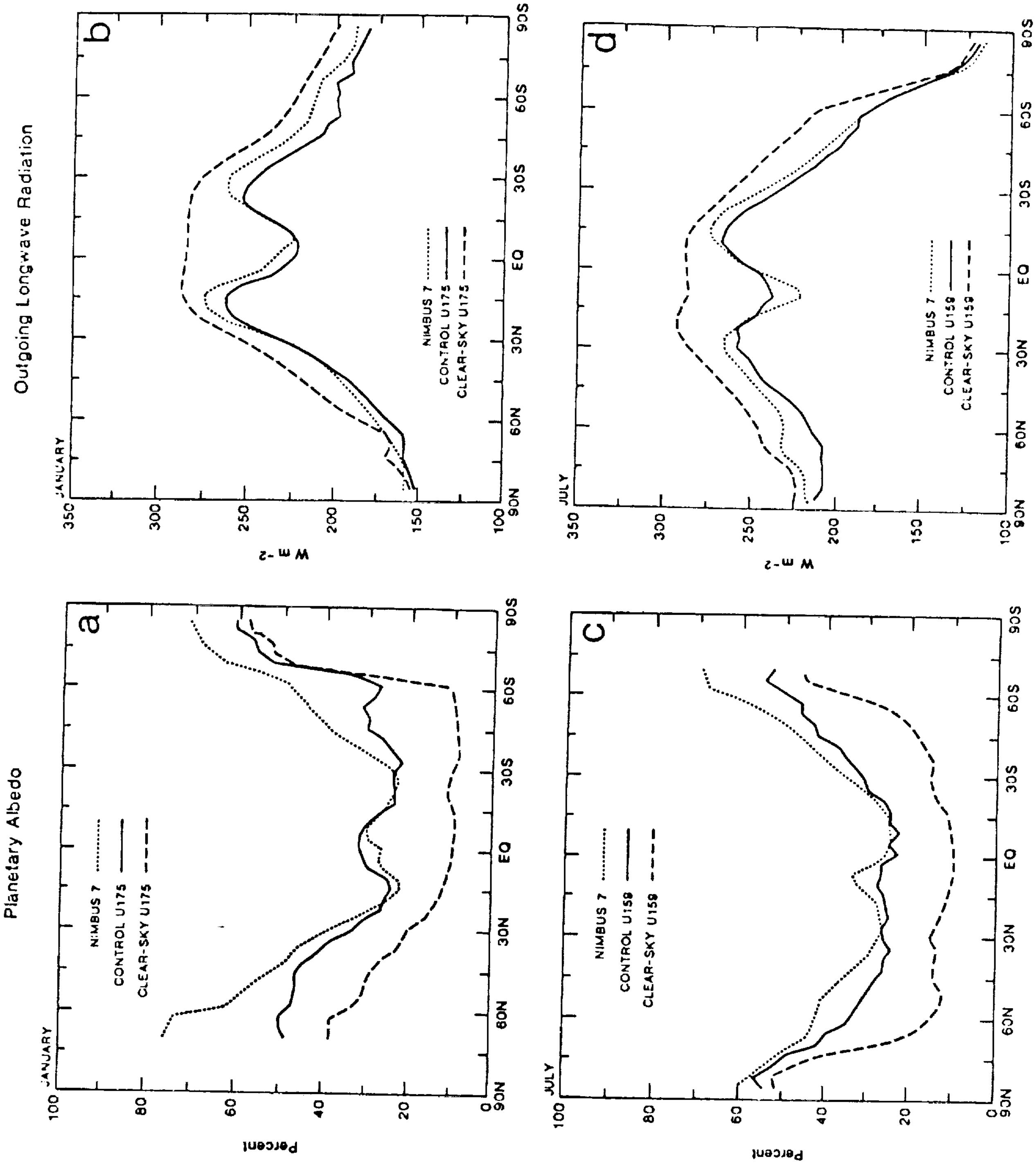

SUB-ARCTIC WINTER
$H_2O + CO_2 + O_3$
— GLA LINE-BY-LINE
- - - GFDL LINE-BY-LINE
o o o GLA PARAMETERIZED
COOLING RATE (°K/DAY)
PRESSURE (MB)
0.01
0.1
1.
10.
100.
1000.
0
2
4
6
8
10
12

FIGURE 1h



Planetary Albedo
Outgoing Longwave Radiation
a
b
c
d
JANUARY
JULY
NIMBUS 7
CONTROL U175
CLEAR-SKY U175
CONTROL U159
CLEAR-SKY U159
Percent
W m-2
90N
60N
30N
EQ
30S
60S
90S

Figure 2

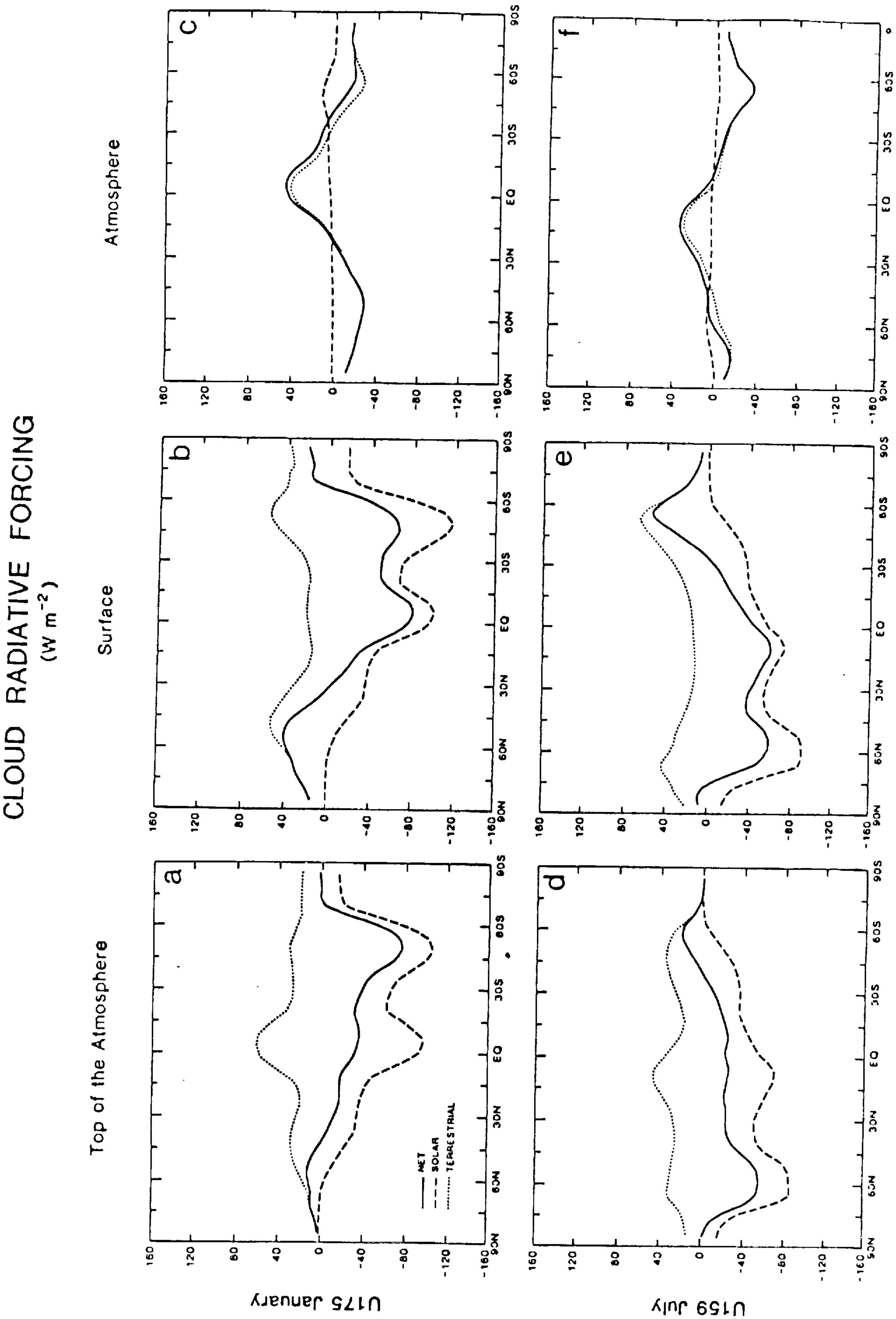

CLOUD RADIATIVE FORCING
(W m^{-2})
Top of the Atmosphere
Surface
Atmosphere
U175 January
U159 July
a
b
c
d
e
f
NET
SOLAR
TERRESTRIAL
160
120
80
40
0
-40
-80
-120
-160
90N
60N
30N
EQ
30S
60S
90S

Figure 3

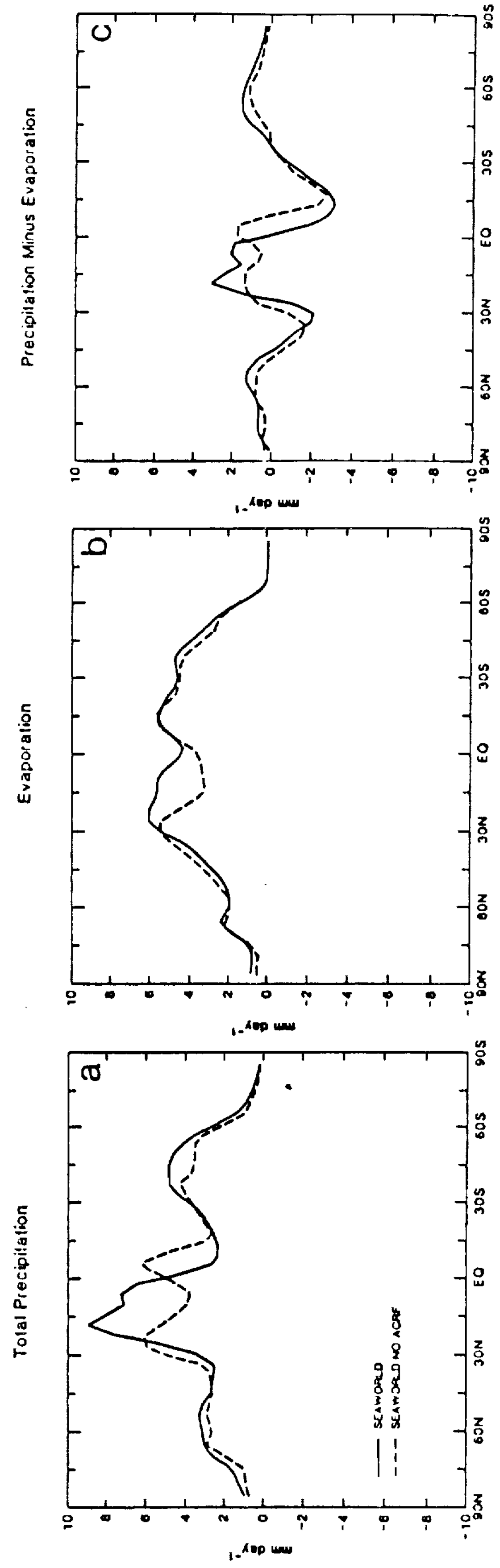

Total Precipitation
Evaporation
Precipitation Minus Evaporation
a
b
c
mm day⁻¹
90N
60N
30N
EQ
30S
60S
90S
SEAWORLD

Figure 4

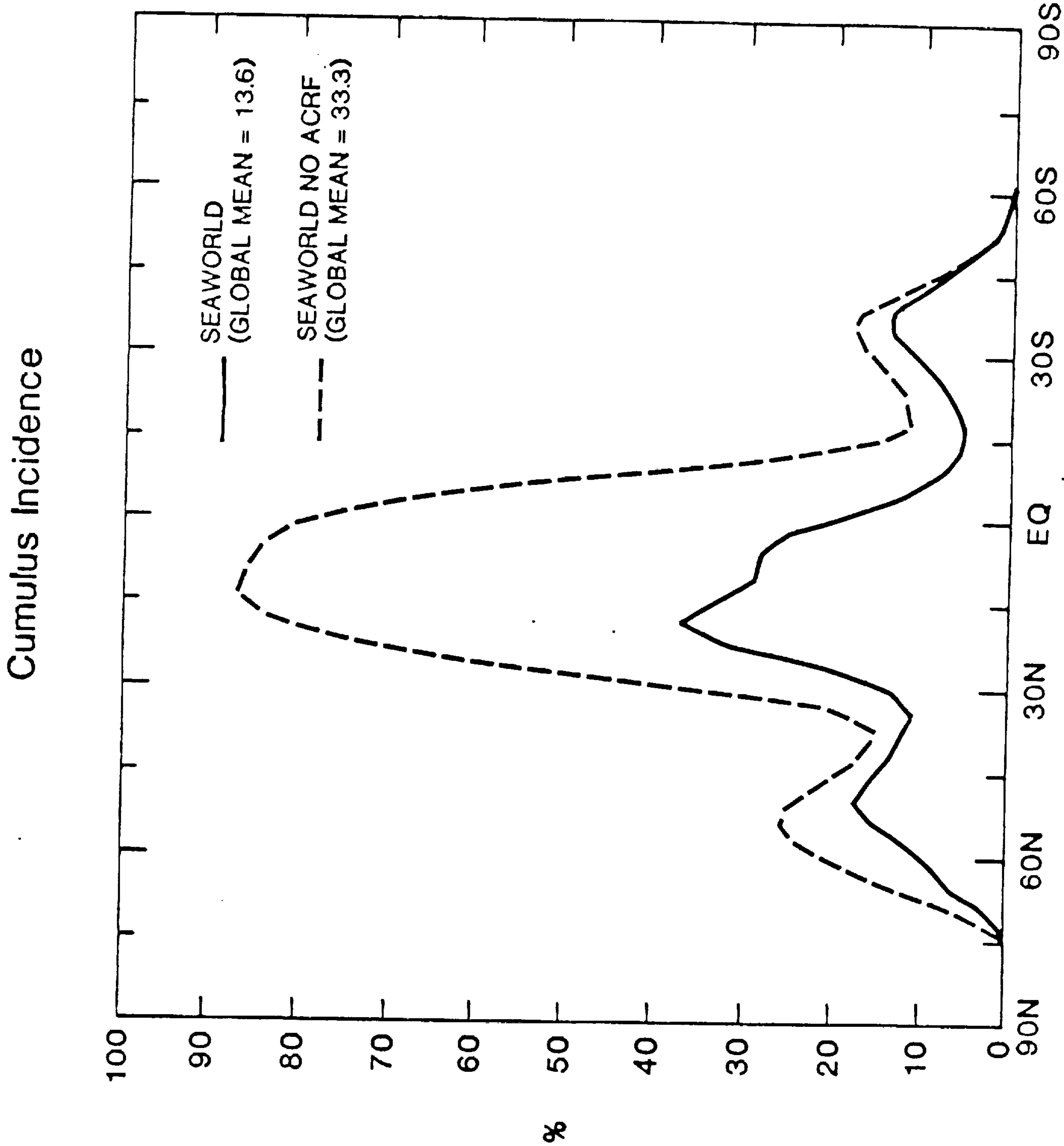

Cumulus Incidence
SEAWORLD
(GLOBAL MEAN = 13.6)
SEAWORLD NO ACRF
(GLOBAL MEAN = 33.3)
%
100
90
80
70
60
50
40
30
20
10
0
90N
60N
30N
EQ
30S
60S
90S

Figure 5

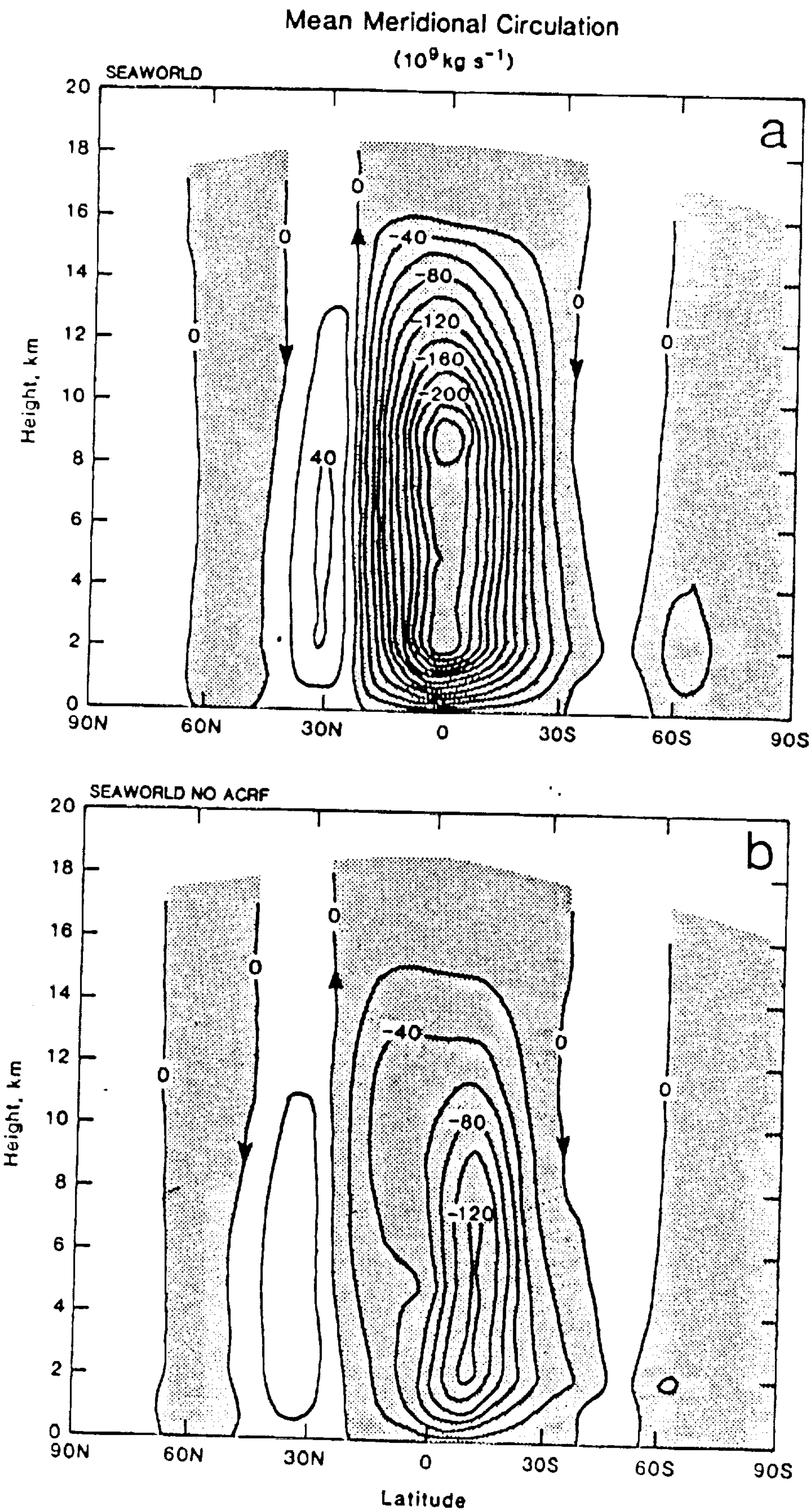

Mean Meridional Circulation
(10^9 kg s^{-1})
SEAWORLD
a
Height, km
20
18
16
14
12
10
8
6
4
2
0
90N
60N
30N
0
30S
60S
90S
-40
-80
-120
-160
-200
40
SEAWORLD NO ACRF
b
-40
-80
-120
Latitude

Figure 6